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THE LIMITS OF SCIENCE LABORATORY ECONOMICS

BY ROBERT C. BUSH

When you entered your first science lab in high school, it was probably not that much different than the lab where your parents had their first taste of "real" science. "Hands-on" was the rule, and experimentation was encouraged in a 30' x 40' room where theory and practice collided to inspire.

For the most part, these were just wet and dry labs. The wet labs were equipped with Bunsen burners, test tubes, and the all-important fume hood. The dry labs had models, weights, rock samples, and various devices that measured in basic dimensions. Both labs had a handful of Zeiss light microscopes tucked away in cases and minimal storage closets for samples and reagents. These lab resources haven't changed much (with a few exceptions) primarily because of the cost to upgrade laboratories.

Realities of Laboratory Economics

On the college level, however, labs are very different. Increased workforce specialization demands comparable specializations in college education. The proliferation of labs includes geology labs, materials labs, hydrodynamics labs, fluid mechanics labs, general chemistry labs, organic chemistry labs, inorganic chemistry labs, microbiology labs, meteorology labs, aerospace labs, and astrophysics labs.

Labs at the college level are still dominated by teaching and learning for 20 to 30 students at a time. Colleges are challenged to keep up with the times, however. Older lab spaces simply cannot be converted to updated, specialized labs mostly because of the physical limitations of the lab room and/or building. Replacement facilities are often the answer, but developing comprehensive funding for these is a huge challenge. Increasingly, replacement science buildings are found at the top of the list for state support or bond funding, where education leaders and policymakers jockey for position among their peers.

Each university research laboratory is unique to its own discipline and set up to conduct research in a paradigm unique to a particular professor. Daily access to a typical university research lab may be limited to a major professor and a post-doctoral student or two who guide experimental design and oversee operation of the lab. A few graduate students and a handful of higher level undergrads are fortunate enough to have a role in the hands-on research that goes on in these labs. By this juncture, these students are a committed core of future scientists. I was lucky enough to be a part of the tribe in a visual psychophysics lab, where complex optical instrumentation combined with behavioral apparatus (such as the ubiquitous "tmaze"), a microscopy and tissue station, a surgical suite, and a PDP-8 minicomputer with several workstations to control instrumentation and crunch numbers existed.

It is not uncommon for a large state or well-funded private university to have scores of such expensive labs that a scant few students and professors use for intensive research efforts. Professors even compete intensively for a wide variety of contracts and grants to support their favorite lines of inquiry, pay for the use of space, and upgrade or buy new equipment. The university administrators must figure out how to convert these many disparate sources of income into justification for suitable facilities to house the most up-to-date labs expected by top researchers. Avenues such as "lease-lease back" design and construction are increasingly popular as means of focusing the many sources of funding.

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At the very pinnacle are the U.S. national labs, such as the Argonne National Laboratory, National High Magnetic Field Laboratory, Fermi National Accelerator Laboratory, or the Lawrence Livermore National Laboratory. The extraordinary expense of setting up and operating these labs means that they are each unique, non-replicative, and exclusive. Consequently, these labs are constructed and run as national strategic resources, often by a consortium of universities with line-item support of the Department of Energy or another federal agency. Even though billions of public dollars are spent annually to maintain and operate these labs, practical access is limited to the top tier of accredited researchers in a given field—Nobel laureates, their peers, and their research fellows.

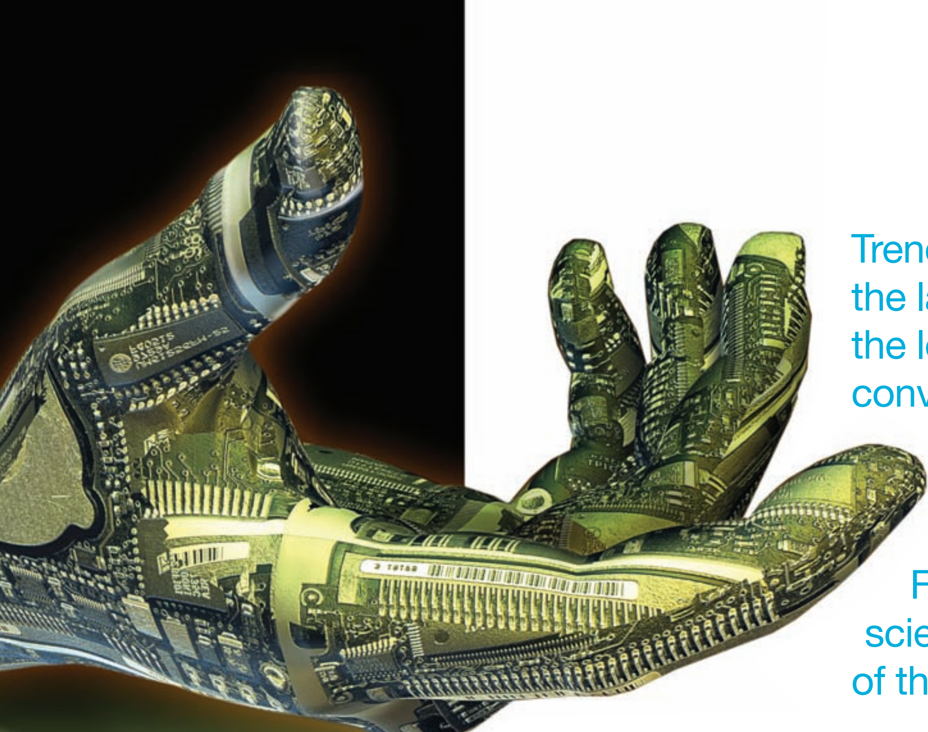
Overcoming the Limits of Lab Economics

Trends are evident; the more specialized the lab, the more expensive it is, and the less accessible it becomes. Or conversely, the more accessible a lab needs to be, the fewer resources can be dedicated per capita, and the less specialized it becomes. From a numerical standpoint, "real" science is in many respects out of reach of the majority of science students. Thus the fundamental question is: "How can real scientific experience be economically offered to today's proto-scientists?"

One approach to answering this question comes from the *virtual lab*. It has been nearly two decades since the first virtual alternatives were offered to students who had ethical or moral dilemmas about "pithing" and dissecting a frog in first-year biology. Over a decade has passed since the first viable "Virtual Frog Dissection Kit" was offered free of charge by authors at the Lawrence Berkeley National Laboratory. While there is tremendous merit to increasingly realistic virtual laboratory "gaming," the virtual world will only take an experimenter so far, since consequences are controlled and limited by programs that do not allow the student to experience real lessons learned.

Another alternative gaining traction is *laboratory modularization*. This solution works best on the "left side" of the laboratory economics dynamic, where higher numbers of students still means overall higher aggregate costs of labs but lower per capita costs. Funding for science facilities at this level is often an artifact of the FTE approach (full-time equivalency students)—where the formulae for distribution of limited construction, maintenance, and operation dollars are based on the number of students served. At this level, working from two basic themes of laboratory— wet and dry labs—means that there is opportunity for modularity. Thomas Register lists no fewer than 300 companies in North America that offer modular laboratory components, units, or related services. There is clearly a trend toward this sort of standardization, as school districts and some community colleges struggle to make ends meet on limited taxpayer allowances. No one is exempt from economic realities.

Colleges nationwide still struggle to find the right balance of cost and capabilities to create compelling environments for students to gain a flavor of differentiated disciplines. Universities compete intensively for government and private grants that will allow them to keep up with the pace of change for high-end equipment and laboratory resources demanded in state-of-the-art research labs. By definition, there are a limited number of institutions that have the political and financial muscle to become national and international centers of excellence, where highly specialized labs are second to none. This all means that a Darwinian bottleneck applies, and there are no easy solutions.



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DaWning age of the ilab

From the perspective of expectations, lawmakers and taxpayers are increasingly impatient to significantly expand the opportunities and benefits of specialized labs for students and researchers—naturally, without a parallel, prohibitive increase in expenditure. A solution to this daunting equation may be found in the conjunction of trends in *telemetry*, *computing* and the *Internet*, *and robotics*—the iLab—a hybrid environment that promises to allow users from anywhere on the planet, or in space for that matter, to access, control, manipulate, and analyze results of scientific experiments that are physically removed from their location.

Telemetry: Just a hundred years ago, many large areas of the United States were still prone to annual flooding. As it is today, prediction was an essential tool to prepare for the worst case. For starters, a pole in the stream was adequate to measure both height and rate of flow. The limited predictability offered by this method was not enough, however, and the USGS began locating measurement and reporting sites further upstream to extend their predictive horizon. Time and staffing required to collect, communicate, and manage data from reporting stations represented a challenge that was overcome after World War II, when the addition of simple radio telemetry "patched" onto local instrumentation allowed remote data collection. Today, there are millions of independent monitoring stations that, without human intervention, send a continuous stream of real-time data to databases that are in turn accessed by computer programs designed to detect anomalies and generate warnings with adequate warning horizons.

Computing and the Internet: When computing first showed up on

college and university campuses in the late 1960s and early 1970s, it was in the form of mainframe machines—heavy iron. Access to computers was limited to high-end users during these early years. Processing was done in heel-to-toe batches, and most involved running manually encoded data (remember the ubiquitous punch-card stacks?) that would be fed in through an ungainly reader, and then processed by simple programs that were written in assembly language and stored on a tape. The work of writing and "tweaking" programs was done on a workstation hard-wired to the mainframe. Graduate students and some higher level undergrads lined up at specified times to collect their printouts. If there was even a small glitch—like a hanging chad or one line of imperfect code—that would mean starting over by manually checking code and data sets, and waiting once again in queue for your print job.

The USGS began locating telemetry sites like these upstream to improve their forecasting of flooding in select areas.

With more demand for university computing resources, data also began to be encoded and stored on large portable discs or tapes. Corrections or changes to data became invisible to the naked eye. Noisy punch-card readers disappeared. Next, parts of programs and in some cases complete programs, began to be shared and were even made available in electronic "libraries." This began to create a level of demand that could not be met with the limited number of hard-wired workstations coupled to any one mainframe computer. Similarly, inefficiencies in heel-to-toe batch processing began to be recognized, since there would be inherent peaks and valleys in processor usage, while each new program was loaded and each data set read in.

It began to dawn on owners of these expensive resources that processor time was the most precious commodity in the equation. Economics are never very far away. Colleges and universities found that additional "dumb terminals" could be added to the computers, allowing the user to initiate programs, call data sets, and watch the results, but programs still had to be written and edited from a workstation hooked directly into the computer. Professors (being professors) found a way to get terminals to work from their offices or labs.

Understanding that there would be little long-term tolerance for dumb terminals, IBM and other mainframe manufacturers begin putting "memory" and a bit of processing power into remote terminals, making them smart. Coupled with the technology that was maturing around the field of telemetry, it was not long before workstations were untethered from their mainframe hosts altogether.

The last piece of the computing/Internet equation was the move from batch processing to timesharing on processors. Instead of heel-to-toe processing of single batches, much shorter segments of code from a variety of programs could be run in priority order, resulting in much more efficient use of processor time. With this breakthrough, college and university computing centers found that they were flooded with requests for "processor cycles" by researchers from all parts of the globe. The bigger and faster the computing resource, the greater the demand.

While the major national labs had been in the game during the earliest, most expensive era of computing, they found themselves becoming centers of attention for another reason altogether. The formidable combined computing resources of the national labs, linked in these new ways, created a new national strategic resource. This first showed up on the horizon as ARPANET and its defense corollary DARPANET, and then ultimately the public Internet.

Robotics: Isaac Asimov's dream of humanoid robots with positronic brains was a far cry from reality when he started writing his famous "I Robot" series in the 1950s. By today's standards, crude actuators and joints have been a part of the manufacturing landscape for some time. Sure, these have removed much of the risk of defects from production, assembly, and processing lines, but are no replacement for their biological analogues—that being us "carbon units." We humans have key attributes that enable us to function smoothly in the controlled settings of scientific laboratories: fine motor manipulation, tactile sensitivity, and visual guidance of our work.

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These areas have received the most attention from researchers in robotics. Advanced robots can now recognize objects by shape and mass, extend arms and articulate joints for microscopic positioning, and use tactile sensitivity to pick up and move objects without crushing or dropping them. The fly in this ointment is the brain. There is still a lot to be done to gain facile, adaptive control of these robotic capabilities. Even the most sophisticated programs designed to enable autonomous operation of advanced robots are far down the food chain from the amazing, adaptive human mind.

An interesting adaptation to advanced robotic capabilities, though, is the human-robot interface. Think of the Mars Rover as a highly sophisticated robot, with some limited decision-making capability "on board." When the Rover met unknown conditions, however, it had to wait for hours while its human operators back in Pasadena, aided by telemetry, figured out what its next move should be and sent a program through the great void, telling it what to do. Closer to home, Space Shuttle astronauts routinely work on the International Space Station—an orbiting lab—moving a robotic boom "arm" by a remote manipulator that translates the human arm movement of the astronaut operator into the galactic proportions of the boom.

Back on earth, robotic technologies have advanced to the degree that most fine surgery is performed by highly skilled surgeons observing their work on a screen that shows a microscopic view of the subject area, and using super-fine instruments controlled by actuators that "step down" the skilled, yet gross movements of the surgeon's hands. More recent is the ability to perform surgery via the Internet. Now being demonstrated, this technology allows a specialty surgeon in Denmark to operate on a patient in Greenland using the same visual field and instrumentation used by surgeons in the same room as the patient—enabled by telemetry and robotics. Economics are the drivers of this equation. It's less

expensive to train a couple of specialists and equip operating theatres with telemetry, the Internet, and robotics than it is to populate the world with specialists.

Opening Game—The iLab Is Alive!

The conjunction of unmet demand for access to advanced labs, telemetry, robotics, and the Internet lead us to a vision of the future where laboratories become shared resources—much like the expensive mainframes of old. A proliferation of "observation stations" are already here. When Dr. Robert Ballard explored the depths of the ocean looking for the remains of the Titanic, he took 5th to 12th graders all over the world with him, live, via the Internet. While scientific workstations are now a ubiquitous part of the landscape, they are still largely doing the same thing they were doing over three decades ago—crunching data. For the most part, workstations that control instrumentation are still found in close proximity to the actual experiments. Add robotics to this equation and this will change, as is transpiring in the medical field.

Famous for its related Artificial Intelligence Labs, the Massachusetts Institute of Technology iCampus Project, with the support of Microsoft, has come a long way in the development of models and resources for prototypical iLabs. In their own words, "iLabs is dedicated to the proposition that online laboratories— real laboratories accessed through the Internet—can enrich science and engineering education by greatly expanding the range of experiments that students are exposed to in the course of their education. Unlike conventional laboratories, iLabs can be shared across a university or across the world. The iLabs vision is to share expensive equipment and educational materials associated with lab experiments as broadly as possible within higher education and beyond. iLab teams have created remote laboratories at MIT in microelectronics, chemical engineering, polymer crystallization, structural engineering, and signal processing as case studies for understanding the complex requirements of operating remote lab experiments and scaling their use to large groups of students at MIT and around the world." (*http://icampus.mit.edu/ilabs/*)

Move over *virtual* and *modular* labs—*iLabs* are coming through.

Bob Bush is a trained psychobiologist and a senior program manager for building programs with Jacobs Carter Burgess, Seattle, WA. E-mail him at *bob.bush@c-b.com*. This is his first article for *Facilities Manager*.